Universitat Autònoma de Barcelona

ENVIRONMENTAL IMPACT ASSESSMENT OF SYNTHETIC NATURAL GAS OF RENEWABLE ORIGIN FROM PILOT PLANT

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Abstract

There is currently a lot of pressure on the transition to fuels with less impact on the environment. The European Commission is applying different directives in order to establish a clear route to greener fuels. Methane can currently be obtained from three routes, the first is to extract it from limited natural wells with fossil origin. The second, currently growing, consists in obtaining from purifying biogas obtained in a renewable way. Finally, in development, is the synthetic gas route. Synthetic gas consists in reacting carbon dioxide with hydrogen to obtain synthetic methane. The present work is devoted to study the environmental impact of the production of this synthetic gas and to compare it with fossil natural gas. The method, used in this study is by the life cycle assessment with the support of a software and the experimental data from a pilot plant on synthetic methane production in the Sabadell (EDAR Sabadell Riu-sec). The pilot plant consisted on using biogas, produced in anaerobic digestion, and reacting it with hydrogen obtained from electrolysis. This allows to obtain a synthesis gas from renewable origin. The work presents different scenarios of possible cases and feasible improvements, studying the different environmental impacts of the cases. The calculated results are that to produce 1 kWh of energy from synthetic gas, 0.412 kg CO_2 eq. are generated in global warming. This value is slightly lower than the traditional production of natural gas from fossil origin. Even so, much work remains to optimize the process energetically because electricity was the main cause of the impact.

Keywords

Renewable gas,

hydrogen,

methanation,

synthetic natural gas,

life cycle assessment

1. Introduction

1.1 Natural Gas

Worldwide carbon emissions from the power sector are growing around 2-3% every year, what indicates that it is a continuously growing sector and one of the main responsible in the climate change. Among fuels, nowadays natural gas is the responsible of 24% of global primary energy consumption of fuel. Natural gas is the third fuel used for the power generation and one of the most used as for heat generation both in industry and in domestic applications. Most natural gas is obtained from fossil origin and thus non-renewable in deep underground rock formations and associated with other hydrocarbon reservoirs [1]. As it can be seen in Figure 1, it is a fuel with an impact with an exponential growth. The increasing demand is due to the easy extraction, use, handling and storage. The potential applications of this gas are also expanding, such as the implementation in mobility instead of using heavier fuels. Transport is one of the main sources of greenhouse gases (GHG) emissions and fuel consumption, thus replacing this gas would have environmental benefits.

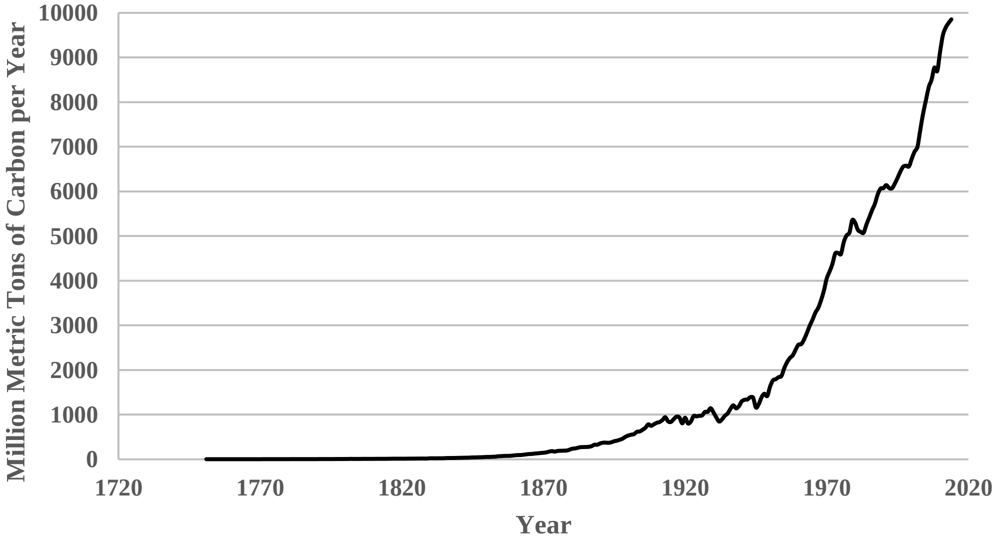

Figure 1. Evolution of CO_2 emissions from fossil fuel combustion. Units: Gigatons of CO_2. Key Point: Since 1870, CO_2 emissions from fuel combustion have risen exponentially [2, 3].

In Spain, natural gas is mainly imported by different pipelines connections and by ships in liquefied natural gas (LNG) form. The main gas connections in Spain are France, Portugal, Maghreb and Algeria. There are 18 LNG storage tanks with a total capacity of 2,337,000 m^3 equivalent to 16,308 GWh [4]. The composition of natural gas found in the network may vary depending on the origin. Mainly it is formed by methane and other alkanes, but it can contain traces of carbon dioxide or hydrogen [5, 6]. For the injection of natural gas into the gas network, a minimum of quality must be met, in the Spanish network a composition ≥ 90% methane, ≤ 2.5% carbon dioxide and ≤ 5 % hydrogen are required [7,8].

1.2 Biomethane

Methane can also be obtained renewably by the fermentation of organic matter, namely biogas. This biogas can be obtained from anaerobic digestion in wastewater treatment plants and from other organic sources as agriculture waste or animal manures [9]. During the anaerobic digestion, the microorganisms degrade the organic material and they produce a mix of biomethane, carbon dioxide and impurities [10]. The low calorific value of the resulting gas imply that this gas must be consumed internally, stored in tanks or burned in case of surpluses because it cannot be injected into the gas network.

Biogas must be converted to biomethane to be injected to the natural gas grid. This process is called upgrading. The upgrading of biogas consists on increasing the methane content that present the biogas source (from 50-65% to 90-97.5%). There are several technologies to carry out the upgrading process, as seen in Figure 2. In recent years, a strong growth in the construction of upgrading plants in Europe can be seen. By 2050, annual sustainable biomethane production could reach 1,072 TWh, which represents roughly 22% of current natural gas consumption. In 2017 there were installed 540 biomethane plants, of which only one was located in Spain. Thus, biomethane in Spain has a huge potential in the following years. In the case of biomethane injection to the gas grid, cost reduction is necessary to compete economically with fossil natural gas [11].

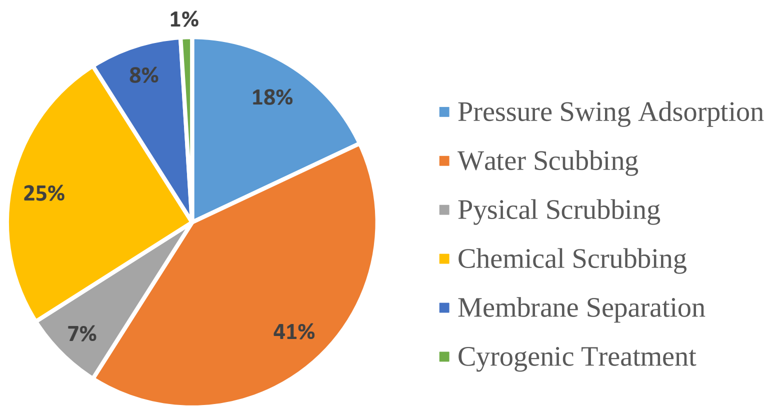

Figure 2. Distribution of biogas upgrading technologies in Europe [12]

The total biomethane production in Europe was 1.23 billion m^3 in 2015 and the raw gas upgrading capacity in Germany rose to 201,265 m^3 per hour by the end of 2016, which corresponds to around 910 million m^3 of upgraded biomethane [12]. State-of-the-art from upgrading biomethane can be divided mainly into two branches. The first is production of biomethane from the separation of CO_2 by adsorption, absorption, membranes or cryogenic distillation. And second option is the CO_2 methanation to produce synthetic gas, in which hydrogen can reacts with carbon dioxide for methane production [13,14]. The product of this last one is called synthetic gas. The second option, synthetic gas, is less mature and implemented than the first one, biomethane.

1.3 Synthetic gas

Besides natural gas extraction and biogas upgrading, a third way to obtain methane gas is through hydrogenation of different carbon sources (Figure 3). Synthetic gas, which is produced by the conversion of carbon dioxide to methane, could be a possible technology in the future. This should be one of the substitutes of the methane extraction from fossil resources and, can be implemented in the anaerobic digesters.

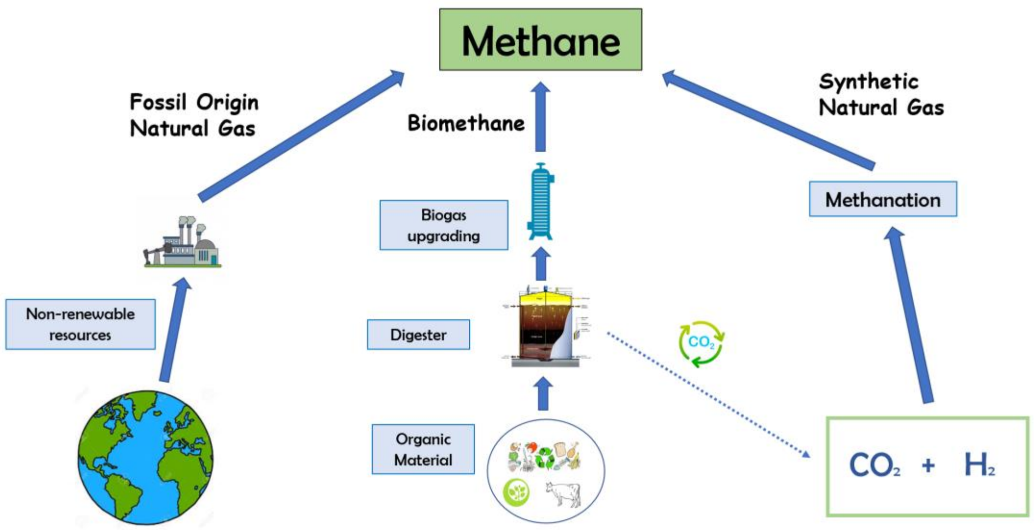

Figure 3. Different paths to reach methane.

One problem with renewable energy, wind and photovoltaic, is to meet production and demand. At present, there are already situations which the amount of energy produced is greater than demand. The storage of this energy nowadays is more expensive and finally ends up wasting it. Hydrogen can play a key role to transform fossil fuel dominated power sectors of today towards a 100% electricity supply by renewable. Due to seasonality of variable renewable energy sources like wind and solar, large-scale seasonal storage is required in addition to other flexibility options such as batteries, pumped-hydro storage and demand-side management, to achieve very high shares of renewable energy on annual electricity supply [15-17]. Hydrogen could be produced when electricity production from variable renewable energy exceeds electricity demand and is stored over several weeks/months until it is converted back to electricity when available variable renewable energy is insufficient to meet electricity demand.

The most recent European legislation approved is the European Directives 2009/28 / CE and 2010/75 / EU, with the aim of reducing air pollutants and greenhouse gas emissions. A transition to renewable and nuclear energy is expected, combining it with a gradual reduction in the operation of coal plants. The long-term objectives are set by two European policies: the climate and energy framework for 2030 and the low-carbon economy by 2050. The first policy establishes a 40% cut in greenhouse gas emissions (compared to 1990 levels) by 2030. The second policy establishes an 80-95% cut in greenhouse gas emissions (compared to 1990 levels) by 2050 [18-21]. It is expected that energy storage will play an important role, compliance with these directives implies a high increase in renewable energy. This augment will produce the problem of excess energy in the most common renewables. The rest of the non-renewable plants have been closed by 2050, despite the combined cycle plants, which operate with maximum load power. Some of them are equipped with carbon capture mechanisms that supply CO_2 to gas power plants, which produce the synthetic natural gas used in these combined cycle plants, resulting in a production of carbon neutral electricity [21]. Even so, other sources of carbon dioxide can be found in industry or in anaerobic digesters large enough for considerable synthetic gas production.

1.4 Environmental impact

The increase of natural production can benefit the environment in many ways compared to other fossil fuels. Natural gas has a lower sulphur and nitrogen content than coal and hydrocarbons, thus using natural gas results in fewer SOx and NOx emissions per kWh of electricity, heat produced and transport. Thus, natural gas has important benefits in terms of air pollution. Additionally, unlike coal-fired power plants, a natural gas combined-cycle system produces no large solid waste streams. The environmental consequences of a power generation facility, though, depend not only on the emissions from the plant, but also those that result from upstream operations such as fuel production and transportation. [22]

However, natural gas is a fossil fuel that emits large amount of CO_2. The decreasing use of fuels such as oil and coal, together with the increase of natural gas [1] make the production of this gas a focus of improvement. Sustainable alternatives as biomethane and synthetic gas with less resource depletion or impact on the footprint are necessary. Accordingly, comparison of the environmental impact is necessary to for making impartial decisions.

1.5 Life Cycle Assessment

Life Cycle Assessment is a technique used to determine environmental aspects and impacts potentials associated with a product. The methodology is based on compiling an inventory of relevant inputs and outputs of the system. Evaluate the environmental impacts potentials associated with those inputs and outputs. Finally, to interpret the results of the inventory and impact phases in relation to the objectives of the study [23].

Life Cycle Assessment is somehow subjective in which it depends on the assumptions and it should be carried out by an external expert. However, is one of the best techniques that allow a good comparison between the different scenarios.

In this study, Life Cycle Assessment was used to compare the environmental impact of synthetic natural gas production compared to conventional fossil natural gas. The data for the construction of the analysis have been obtained from the experiences of a pilot plant. An analysis of an industrial production would be more detailed due to space distribution but, in terms of products and consumables, the production in the pilot plant can be scaled up to an under production. In any case, large-scale production should be more optimized, therefore the results have less impact than those obtained. It is very important to have experimental data because the Life Cycle Assessment has may contain data resulting from subjectivity. Therefore, the use of empirical data obtained with the best practices gives more firmness to the comparison and validation of the results.

2. Objectives

The objective of this project is to evaluate the environmental impact of the production of synthetic gas produced from CO_2 by methanation and to compare it from the natural gas of fossil origins. Different scenarios are proposed:

1. Determine the environmental impact of synthetic natural gas production from the experience obtained in a pilot plant located in EDAR Riu Sec (Sabadell).

2. Comparison of the impact between natural gas from fossil origin and synthetic gas by methanation.
3. Evaluation of plausible future scenarios for synthetic gas as:
   - Different source of electricity.
   - Type of electrolyzer.
   - Different CO_2 source.
4. Discuss the suitability of investing in synthetic natural gas technology from an environmental point of view

3. Methodology

The method, used in the study, was the life cycle assessment with the support of the Life Cycle Assessment software. The software was previously developed for this type of environmental studies and allows from the organization of inventories and sub-stages until the calculation of the impact in different categories. The data used have been based on the experiences and experimental data obtained from the pilot plant about synthetic methane production in the Sabadell treatment plant (EDAR Sabadell Riu-sec).

The pilot plant (Figure 4) was managed by CoSin project (Synthetic Fuel) co-funded by ACCIÓ and the European Regional Development Fund (FEDER) under the RIS3CAT Energy Community. The synthetic gas action was partner collaboration between the Catalonia Institute Energy Research (IREC) and Naturgy (formerly Gas Natural Fenosa). The Life Cycle Assessment software was developed by Inedit [24] and Precision within the LCAEnerboost project, also funded by ACCIÓ.

The pilot synthetic gas plant used the biogas produced from the digesters at the EDAR Riu Sec in Sabadell (Spain). The wastewater treatment plant processed municipal water from 200,000 equivalent inhabitants with an average flow of 33,000 m3/day, obtaining 100 Nm3/h of biogas in the anaerobic digestor process. However, the available flow was 80 Nm3/h because the rest was consumed to achieve the anaerobic digester temperature [25].

3.1 Process description

The distribution of the equipment installed for this process is shown in Figure 5. It can be seen the different stages of biogas upgrading, this process is mainly composed by four parts, drying, cleaning and compression, electrolyzer and finally methanation.

Figure 4. General view of Cosin pilot site: (a) catalytic methanation (b) biogas membrane upgrading and (c) biogas cleaning unit.

In the catalytic methanation container, the main reaction (Equation 1) was carried out by the catalytic-conversion of hydrogen and dioxide of carbon at moderate condition of operation, a range of 250 - 500 ºC of temperature and 6 bars of pressure, with a nickel-based catalyst. The whole process was divided into different stages.

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O \qquad (1)$$

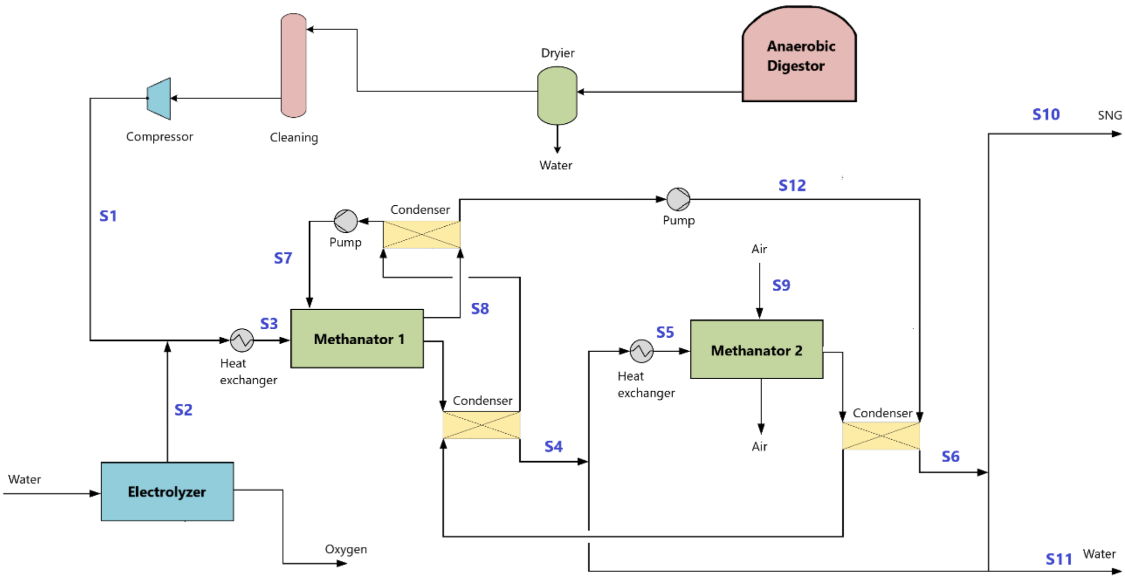

Figure 5. Diagram of SNG production from the biogas of an anaerobic digester

3.1.1 Cleaning

The anaerobic digester produces methane with impurities such as H_2S, BTEX, NH_3 VOCs, siloxanes and BTX [26] then the raw gas passed thought different stages with the objective to clean the mixture.

The first stage was a filter of active carbon with objective to eliminate sulphur and organic compounds. Coming up next, there was a separation of the water. This separation was done by cooling to -5 ° C of the flow by glycerol mixture. Between the water separation and the compressor there was a buffer tank that ensures a minimum flow for the start-up of the compressor and allows gas recirculation in case there is little flow. The compressor increased the pressure up to 6-10 bars to cope with the loss of it during the process, increase the kinetics of the reaction and be able to inject into the gas network.

3.1.2 Hydrogen production

Hydrogen was produced in-situ in the pilot plant. A stream of tap water was deionized and introduced to an electrolyser, which produced hydrogen and oxygen through electricity from the gas grid (Equation 2). Oxygen was speared out and hydrogen was mixed with the biogas stream. We can see the hydrolysis machine and the rest of the following equipment in Figure 6.

$$2\,H_2O \rightarrow\ 2\,H_2 + O_2 \qquad (2)$$

The electrolyzer used for hydrogen production was based on the commercial alkaline technology (Erredue), with a consumption of 37 kWh_e. The efficiency from the electrolyzer use was around 56%. It should be pointed out that most of the energy necessary to produce the synthesis gas was consumed at this stage (about 85-90%).

3.1.3 Methanation

The conversion of the CO_2 from biogas and the hydrogen from water was carried out through chemical methanation. A heat exchanger upgraded the temperature from 20ºC to 350ºC and by electrical heating inside the reactor the temperature was improved until 500ºC, the operation conditions. The temperature was maintained from the control of water flow that enter inside a cooling jacket. Table 1 describes the characteristics of the different process streams.

Table 1. Description of process streams from Figure 1. Biogas (BG), hydrogen (H2), biogas with hydrogen (SG), water (W) and steam (ST).

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Vol. Flow [Nm³/h]	4.25	6	Var.	Var.	Var.	Var.	0.005	0.005	Var.	Var.	Var.	0,5
Temperature [ºC]	20	20	350	50	350	50	233	330	<30	50	50	50
Pressure [bar]	12	>6	6	6	6	6	30	30	1	6	1	2
Medium	BG	H2	SG	SNG	SNG	SNG	W	ST	Air	SNG	W	W
Mass flow [kg/h]	5.17	0.54	5.71	5.71	3.36	3.36	5	5	Var.	3.23	2.48	500

The cooling water was converted into steam, it passed through a loop of condensers in which it was counted to introduce to a second reactor. On the other hand, most of the carbon dioxide has reacted but along with the rest, must pass to another reactor. Between the two reactors, the process water was separated by a condenser. Other heat exchanger increased the temperature to 350ºC, analogously as the first reactor. The reactor temperature, this time, was controlled by an air flow rate at 50 °C. Finally, water produced was separated by another condenser. Outlet the condenser, pressure of synthetic natural gas was a little less 6 bar. The pressure required to inject inside gas distribution stream was 5 bar, then synthetic gas could be injected to gas network without an additional compression. For safety reasons there was a nitrogen steam that could be injected to the proses for inertization, also there was some pressure safety valves in the most critical parts of the process that could be open if the pressure increases sending process fluids to the environment.

Figure 6. Imatge of the distribution of the synthetic gas pilot plant of the EDAR Riu Sec (Sabadell). (a) Condensers (b) Reactors (c) Electrolyzer.

After that biogas has passed through the described methanation process, the synthetic gas presented the desired quality to be injected into the national gas network, as shown in Table 2. Thus, during the Cosin project it was validated the technology of synthetic gas production. This study will evaluate the environmental impact of the production of this synthetic gas.

Table 2. Component fractions in the process boundaries [26] and minimum gas quality from unconventional sources into the Spanish gas system [6,7]

components	**inlet**	**outlet**	**quality requirements for injection**
CH_4	63-65	96.11	≥ 90
CO_2	35-37	2.11	≤ 2.5
H_2	-	1.77	≤ 5

3.2 Life cycle analysis

3.2.1 Functional unit

The functional unit is a key element of LCA which has to be clearly defined. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables comparison of two essential different systems. Definition of a functional unit could be difficult. The definition should be precise and comparable enough so that the unit can be used throughout the study as reference. Herein, the functional unit as 1 kWh of methane produced was chosen. Considering the heating value of the product composition, this corresponds to 0.1 Nm3 of synthetic gas.

3.2.2 System boundary

The main boundaries that have been raised were: the inputs of the process consumables, the transport of the them, the treatment of the waste of the most significant main compounds and the construction of the process equipment. In terms of the process, it was considered from the exit of biogas in the anaerobic digestion until its final use. Figure 7 presents the outlines of the different boundaries of the system. The two raw materials inputs were mainly biogas and water. The biogas came from the anaerobic digestion. Water came from the water network. In each stage, it can be observed the energy or the different consumables necessary for each stage to work. The different uses of methane considered are shown in the outputs.

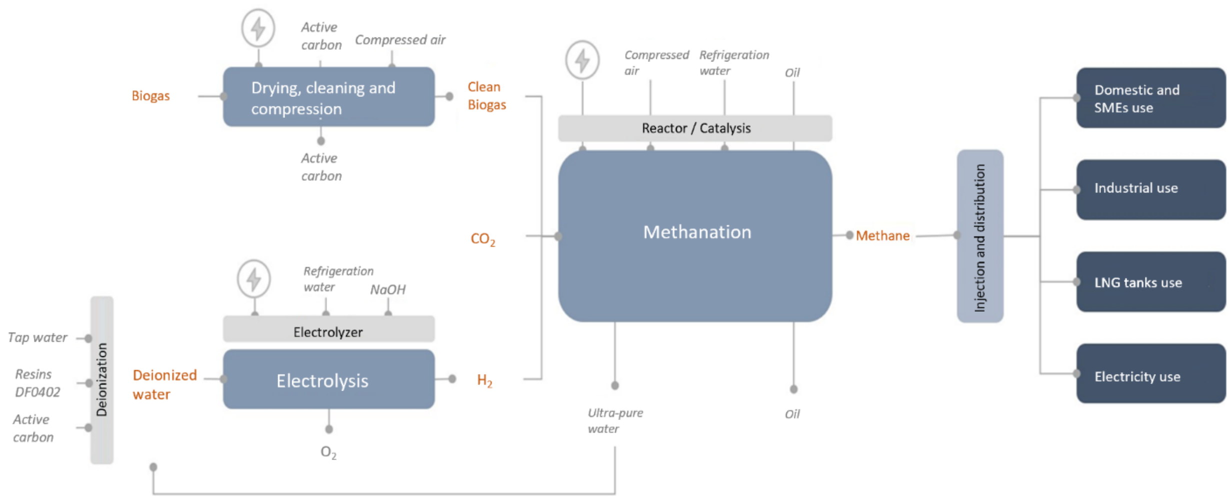

Figure 7. The boundary of synthetic natural gas by methanation system studied.

3.3 Inventory

Table 3 presents the inventory used for life cycle analysis. As noted, it was differentiated in stages belonging to each process-unit.

The desalination of water, necessary for water hydrolysis, uses active carbon filters, polymeric membranes of polysulphonates of polyvinyl and polyacrylonitriles and finally, a 31% anionic and 69% cationic resin. For the biogas conditioning, energy is mainly needed for the dehydration and compression of the biogas together with the active carbon filter. This section also includes transportation and treatment for active carbon. Consumables such as cooling water, electricity, caustic soda and nickel electrodes are needed for electrolysis. In the methanation, the construction of the equipment such as the reactor, the pipes and the different necessary instrumentation has been considered. This was calculated assuming a useful life of 20 years and a workload of 98%. A possible recycling of this material at its end of life has not been considered. It has considered the consumption of catalyst in each life cycle, this, is composed of a mixture of nickel, cerium and alumina [27]. The consumption of utilities such as cooling water, electricity or air used to move the different instrumentation of the pilot plant.

Deionized water is brought from filters; therefore, different types of polymers and active carbon are used. In the initial part of the process, a consumption of active carbon has been considered for the laundering of biogas, dry and compressed air for dehydration and also, the energy needed to achieve compression at operating conditions. Electrolysis is mainly done with deionized water, caustic soda and the energy requirements necessary to carry out the hydrolysis reaction.

Finally, it has considered the different options in which this fuel is consumed, from domestic, commercial or industrial use. However, the renewable character of the synthesis gas produced does not influence the impact. In terms of Life Cycle Assessment philosophy, the hypothesis is that the biomethane used had no impact because it was from biogenic origin. This biogas came from the sludge of the WWTP and its current purpose was to store it for internal consumption or burn it in the flare, causing current CO_2 emissions equivalent to those that would occur in the combustion process in the case of synthesis gas. In terms of stoichiometry, a carbon dioxide molecule is needed to produce a synthetic methane molecule and on the other hand the synthetic methane when combustion generates a carbon dioxide molecule, therefore all the reacted CO_2 has no impact. In contrast, the process to produce this gas has impact, which is the main objective of this study.

Table 3. Inventory of the production process of synthetic gas used in the life cycle assessment

Stage	Element	Consumption	Units
Biogas			
	Inlet biogas	0.65*	kWh
Deionized water			
	Tap water	0.11	kg
	Resin DF0402	$5.18 \cdot 10^{-5}$	kg
	Osmosis activated carbon	$4.32 \cdot 10^{-5}$	kg
	Osmosis polymer membrane	$6.48 \cdot 10^{-5}$	kg
Drying, cleaning and compression			
	Activated carbon material	$1.11 \cdot 10^{-5}$	kg
	Activated carbon transport	$2.21 \cdot 10^{-7}$	tkm
	Compressed air	$1.99 \cdot 10^{-8}$	m^3
	Gas dryer	$9.54 \cdot 10^{-6}$	kWh
	SNG compressor	0.016	kWh
	Activated carbon waste	$1.11 \cdot 10^{-5}$	kg
Electrolysis			
	Cooling water	78.97	kg
	Caustic soda solution (NaOH)	$1.16 \cdot 10^{-3}$	kg
	Electrolyzer - 99.5% Ni	$5.81 \cdot 10^{-4}$	kg
	Electrolyzer electricity	0.97	kWh
Methanation			
	Cooling water	$2.28 \cdot 10^{-4}$	kg
	Compressed air	$2.11 \cdot 10^{-2}$	m^3
	Thermal oil	$1.16 \cdot 10^{-3}$	kg
	Total steel	$6.76 \cdot 10^{-3}$	kg
	Catalyst - 25% Ni	$1.06 \cdot 10^{-5}$	kg
	Catalyst - 20% Ce	$8.49 \cdot 10^{-6}$	kg
	Catalyst - 55% Al_2O_3	$2.33 \cdot 10^{-5}$	kg
	Electricity for methanation	0.16	kWh
Biomethane use			
	DC biomethane use	0.18*	kWh
	Industrial biomethane use	0.57*	kWh

GNL cisterns biomethane use	$3.25 \cdot 10^{-2}$*	kWh
Thermal power plant biomethane use	$6.47 \cdot 10^{-4}$*	kWh
Combined cycle biomethane electricity	0.22*	kWh

* *Materials and electrical consumptions that have been taken into account but have no impact on the life cycle assessment.*

3.5 Impact categories

The impact categories are very broad and, depending on the nature of the study, are generally sub-divided to represent more specific impacts. The European Environment Agency [28] identifies abiotic resources, biotic resources, land use issues, global warming, stratospheric ozone depletion, ecotoxicological impacts, human toxicological impacts, photochemical oxidant formation, acidification and eutrophication. The respective impact factors for each inventory material have been obtained from the software developed by Inedit and Precision within the LCAEnerboost project. The categories studied for this work are the following:

- Energy use (MJ): Contributes to depletion of renewable and non-renewable energy resources.
- Global warming (kg CO_2 eq): Contributes to atmospheric absorption of infrared radiation.
- Exhaustion of abiotic resources (MJ): Contributes to depletion of non-renewable resources.
- Acidification (kg SO_2 eq): Contributes to acid deposition.
- Eutrophication (kg P eq): Provision of nutrients contributes to biological oxygen demand.

In the present study, the efforts were driven to the global warming category. This is undoubtedly the most worrisome and on which most environmental studies of life cycle assessment are based nowadays due to the climate emergency.

4. Results and discussion

4.1 Current scenario.

This section presents the results for the baseline scenario. This case is claimed considering that the source of energy comes from the current Spanish electricity grid (2019). The impact of using 1 kWh of synthetic gas represents a global warming value of 0.412 kg CO_2 eq. With regards to the rest of the impacts, an energy use value of 12.333 MJ and exhaustion of abiotic resources of 6.958 MJ were obtained. Furthermore, with not so significant values, acidification of 0.006

kg SO_2 eq. and eutrophication of 0.0008 kg P eq. Figure 8 shows the comparison of the different stages of the process and the impact they have on the different environmental scenarios studied. The electrolysis of water and methanation are the stages that generate the most impact. This is a consequence that these two stages are the main consumers of electricity making the impact increase compared to the different consumables.

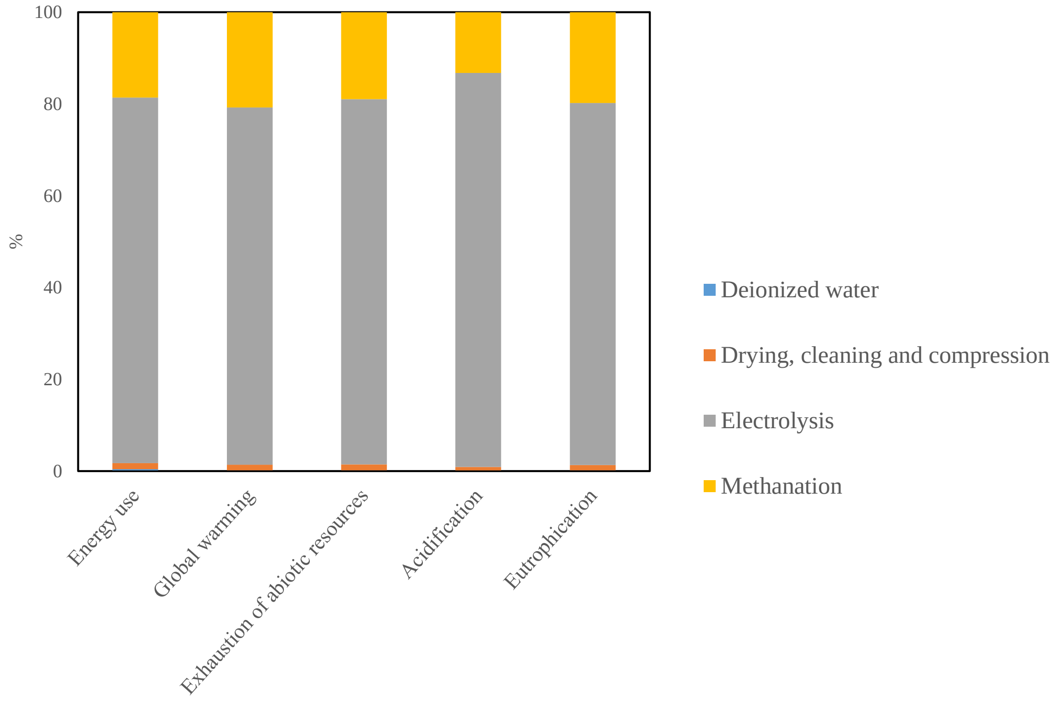

Figure 8. Comparison of the total impact of the production of SNG in its different stages.

Electricity consumed by the electrolyser for hydrogen production is the utility that has the most impact. A value of 0.97 kWh of electricity from electrolyzer are necessary for the consumption of 1 kWh of synthetic gas, showing that the process is not very energy efficient. This means that the energy optimization in the production of synthetic gas can achieve an environmental improvement in parallel, being able to further reduce the footprint impact.

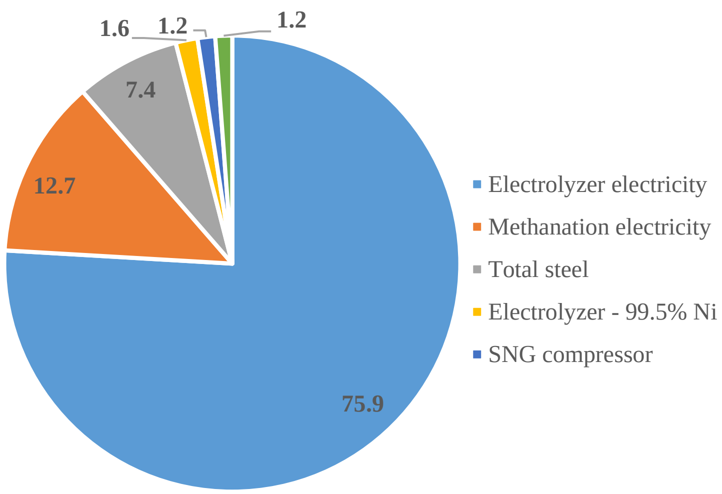

Figure 9. Main inventory components that have an impact on global warming.

Figure 9 shows the main components and its impacts on the global warming. It is possible to distinguish mainly one block, the electric consumption from electrolyzer with an impact of 76%. This category is followed by methanation electricity, whose is less than electrolyzer, and those of consumables (steel, nickel and others). Steel used for the construction of equipment in the methanation reaction stage is the third part of the inventory that has the greatest environmental impact. This is due to a scale up effect, the data of the steel used has been obtained from a pilot plant where the production flow rate was quite low (between 4 and 6 Nm^3 / h). If the production were greater, that is, the equipment was proportionately larger, more flow could be produced and proportionally less steel would be needed for every 1Nm^3 / h of synthesis gas. The energy used for methanation could be reduced with an improvement of the catalyst, allowing a better conversion or a reduction in operating conditions. In the case of electrolysis, an improvement in the efficiency of the equipment would reduce the electricity consumed, causing the greatest reduction in the impact on climate change. Therefore, this will be a focus in the study.

4.2 Fossil-origin comparison.

In this section, the environmental impact of synthetic gas is compared with that obtained from fossil origin. As a basis for comparison, the life cycle assessment for 1kWh of natural gas with fossil origin was considered. Thus, if compared with the other values found in the bibliography, can be seen that it is much smaller than the others. Therefore, for comparison in global warming, it has been decided to average the results obtained and those found in the literature, getting a value of 0.523 kg of CO_2 eq.

Table 4. Different values of LCA for 1kWh produced from natural gas of fossil origin with similar boundaries.

Life cycle assessment	kg CO_2 eq/KWh	Process type
Spath [32]	0.493	Conventional
Venkatesh [33]	0.476	Conventional
Burnham [34]	0.620	Conventional
Burnham [34]	0.589	Shale Gas
Jiang [35]	0.507	Shale Gas
Marcellus [32]	0.453	Shale Gas
Average	0.523	-
SNG from pilot plant (this study)	0.412	Methanation

The effect of the footprint on the climatic change that has the production of natural gas from fossil origin during the last decades there has been an increase of more than 40% in the footprint [29]. Natural gas processes have been optimized to obtain better yields and its renewed technology to take full advantage of the components. Even so, the increase in demand for this fuel unleashes in a respective increase in its impact on global warming. In the other case, synthetic natural gas, the value obtained has been 0.412 kg of CO_2 eq, which is 79% of fossil origin. Considering that global greenhouse gases are the main problem of climate change, a reduction of 21% is quite interesting. This fact indicates that the production of synthetic gas not only allows the lowest consumption of materials from fossil origin, but also, with more sustainable productions. In symbolic terms, as seen above, the use of combustible for transport, industrial or domestic use is one of the main causes of climate change, with approximately 40% of global emissions [30,31]. If the use of natural gas is the 24% for this used fuel, replacing natural gas with synthetic gas would decrease the impact on global warming of approximately 1.6%.

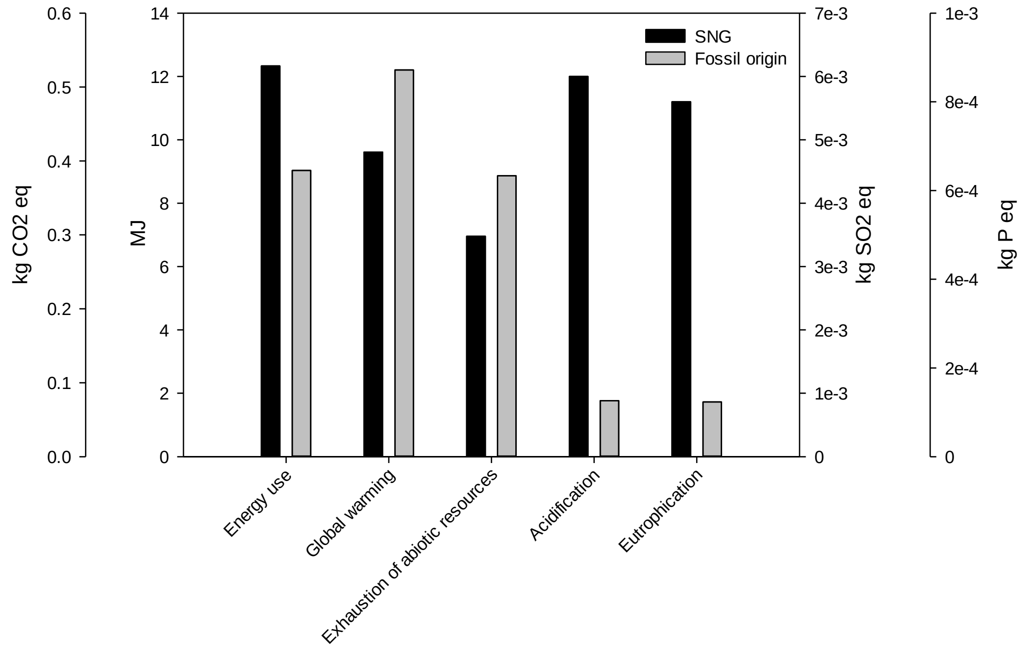

Figure 10. Comparison of the total impact of the production of SNG and fossil origin. Energy use [MJ], global warming average [kg CO_2 eq], exhaustion of abiotic resources [MJ], acidification [kg SO_2 eq] and eutrophication [kg P eq]. Life cycle inventory from fossil gas data not shown

Figure 10 contains the results of the comparison between synthetic gas and that obtained from fossil origin. As regards to the other environmental impact categories the energy demand between the production of synthetic gas, 12.33 MJ, is lightly higher than the fossil gas, 9.030 MJ. Refinery production usually consume a large amount electricity but, on the other hand there are a lot of process alternatives to recover this energy as cogeneration, which can produce up to 53% of the plant's internal energy demand [36]. As we can see form the synthetic gas process there are some equips as compressors, pumps, electrolyser or electrical heaters that consume electricity and unlike refinery there is not any process to recover this. Following with this, synthetic production seems that has less impact on climate changing and on the exhaustion of anaerobic resources than the fossil production. This may be because synthesis gas not only produces a fuel, but also consumes CO_2, which is one of the main protagonists of global warming. Acidification and eutrophication seem that synthetic gas production impact more rather refinery but both, are too small to be compared.

4.2 Future scenarios.

4.2.1 Electric sources.

The electricity mix is constantly changing. In this sense, greener electricity sources are displacing the more pollutant ones as carbon power sources. A representative example is that carbon-based electricity has almost disappeared in Spain during 2019.

In this section is calculated the life cycle analysis considering different sources of electricity. Previously, it was presented that for the base case a value of 0.412 kg CO_2 eq. has been obtained, this considers a mix of energy from the Spanish network of 2018 in which a renewable part is considered, another from the nuclear one and from various sources. If we consider that electricity comes from 100% renewable, the global warming impact value is reduced by 76%, obtaining a value of 0.099 kg CO_2 eq. The environmental impact of synthetic gas decreases significantly as the most relevant process consumables is the electricity. These values show, once again in the literature, that a transition to renewable energy or fossil fuels with less impact than the one in the current Spanish electricity network leads to a very significant reduction in the impact on any process where its main impact is the electricity.

Figure 11 shows the different impacts obtained according to each scenario. In the case of fossil origin, the impact that electricity has on the process is even greater than the production of synthetic gas. Therefore, a transition to renewable energy would favour much more synthetic production compared to fossil origin.

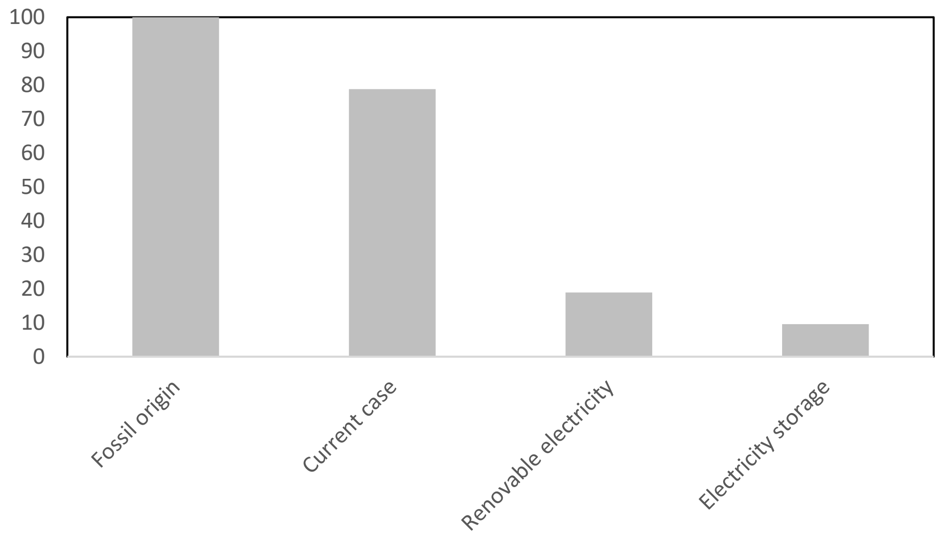

Figure 11. Compression between methane production form fossil origin, methanation process and methanation process as energy storage. The first scenario takes a value of 100. The other scenarios show the impact as a percentage value relative to the first scenario.

Another scenario has been proposed in which the production of synthetic gas is given with the aim of energy storage. Taking advantage of energy overproductions, which have renewable energy, to produce synthetic gas. In this case, the energy consumed has no impact because it will be energy that would be lost. Obtaining results 0.05 kg CO_2 eq environmental impact. This is ideally the lower value that could be obtained. This scenario differs from the renewable electricity one, as in this case the impact of the production of electricity, although renewable, was not taken into account. This case is an extreme of optimistic scenario as the considered methanation process workload of 98% then is not realistic. However, it is interesting to show the two extremes: fossil natural gas and synthetic only as energy storage.

In conclusion, the source of electricity is very important. If the electricity is from renewable sources, the impact can be reduced up to 76%. According to the European Union there is a route for more renewable electricity production. The European Commission has expectations for 2030 to reduce the impact on greenhouse gases by 30% [20]. This would mean a 23.4% reduction in the environmental impact on the production of synthetic gas. In legislative aspects, European directives tend to favour the production of synthetic gas. It can be deduced that the production of synthetic gas has the potential to be one of the great methods of transition to cleaner production. Even so, there is still a lot of engineering to optimize electricity consumption and make this process firmer for industrial scaling.

4.2.2 Electrolyzer efficiency.

As aforementioned, the higher electricity consumption of the electrolyzer is the cause of the greatest impact during the process. The used electrolyzer was a alkaline electrolysis cells (AEC) technology and it has an efficiency of 0.561. Even so, water electrolysis technology is currently under development with a high range of R&D efforts. Polymer electrolyte membrane, solid oxide electrolysis or alkaline electrolysis are technologies with high research, having expectations for 2020 to achieve productions at 50 kWh/kg while the current one is around 55 kWh/kg [37]. Table 5 shows different types of electrolyzer and its updated efficiencies (2019). It is considered that hypothetically it can be reached at a maximum of 90% efficiency.

Table 5. Different values of LCA for 1kWh produced from natural gas of fossil origin with similar boundaries. Data from the providers technical specifications.

Company	Location	Technology	Efficiency
Sunfire	Denmark	SOEC	0.811
Siemens	Germany	PEM	0.750
Areva	France	PEM	0.682
McPhy	France	AEC	0.667
Actaspa	Spain	AEC	0.625
H-TEC	Germany	PEM	0.612

Nel	US	PEM	0.606
Giner	US	PEM	0.600
H2B2	Spain	PEM	0.588
Hydrogenics	Canada	AEC	0.577
Erredue (Present case)	Italy	AEC	0.561

Figure 12 shows the environmental impact that the different types of commercial electrolyzer led to. For the current case an impact was obtained in the global warming of 0.412 kg of CO_2 eq. If a more efficient technology were used as the SOEC from Denmark, the impact could be reduced to 0.316. This would mean a reduction of 23.4% of the total. In addition, a hypothetical case of 90% efficiency in water electrolysis would mean a 28.6% reduction in impact compared to the current one. Nevertheless, the investment costs of a SOEC or a high efficient PEM electrolyzer is still much higher than the AEC technology implemented in the current project. In any case, future improvements in electrolysis technology will impact severely on the environmental impact. Accordingly, the use of new electrolyser technology reduces significantly the environmental impact of synthetic gas.

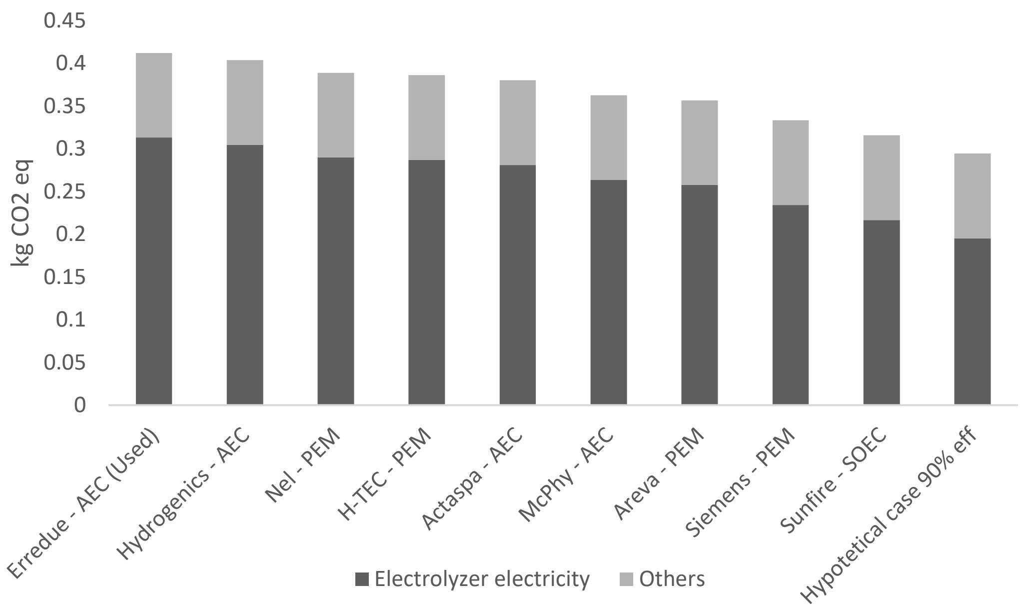

Figure 12. Impact on global warming depending on the type of electrolyzer.

4.2.2 CO_2 source.

In this section, a different the source of CO_2 is considered, instead of coming from an anaerobic digester, comes from a source of pure CO_2. For instance, this hypothesis encompasses all the CO_2 capture processes. Representative examples can be capture from a combustion process (biomass or fossil fuel), direct air capture, utilization of the released CO_2 of the biomethane upgrading plants or CO_2 from alcohol fermentation (bioethanol, beer, wine).

In the base case, the composition has 65% methane for every 25% CO_2. This means that the energy to convert 100% CO_2 will be almost three times higher for the pure case. A value of 1.535 kg of CO_2 eq was obtained, even though it considers the operation in the pilot plant designed to have an entry with biogas, where the operation is even simpler. The high environmental impact is because the electricity consumption of the electrolyzer increases almost 4-times, from 0.96kWh to 3,9 kWh for every 1 KWh produced. However, these are the pilot plant operating conditions. Optimization of the electrolyser at one of 81.1% efficiency could reduce consumption to 2,7 kWh. If it is also considered that the electrical source comes from renewable energies, the global warming value could be reduced to 0.22 kg CO_2 eq. If this value is compared with the production of fossil origin, which is 0.523 kg of CO_2 eq, it is obtained that the production of synthetic gas with a source of pure CO_2 has an environmental impact of 58% less than that of fossil origin. Apart from not mentioning that fossil sources are limited resources with an expiration date.

Thus demonstrating, a good practice of operation with a source of pure CO_2 makes this technology an environmentally friendly technology in the fight against global warming. Being able to use it to clean areas with high CO_2 load and producing energy with renewable sources. In any case, the utilization of pure CO_2 as carbon source is 3-times less beneficial than biogas. Accordingly, the latter source should be preferred in terms of environmental impact.

4.2.3 Combined scenarios

Table 6 shows an abridgment with all the scenarios studied in order to make a global comparison. In summary, the production of synthetic gas has less impact than conventional production of fossil origin. As an exemption, using a pure CO_2 source with the Spanish electricity grid of 2018 showed greater impact. The rest of the case of studies, the production of synthetic gas was favourable. Notably, an improvement in the electrolyzer efficiency and the use of renewable energy reduces impacts by almost a third. The lowest environmental impact is obtained when using renewable electricity, an advanced electrolyzer and biogas as carbon source. In this case, the impact on global warming is 0.076 kg of CO_2 eq. That means a reduction of 85% of the environmental impact.

Table 6. Comparison of the different scenarios

Scenario	Emission (kg CO_2 eq/KWh)
Pure CO_2	1.535
Fossil gas	0.523
Synthetic gas (current case)	0.412
Advanced electrolyzer	0.316
Ren. electricity and advanced electrolyzer (Pure CO_2)	0.22
Renewable electricity	0.099
Ren. electricity and advanced electrolyzer (biogas)	0.076

5. Conclusions

The production of synthetic gas is feasible from a technical point of view. From this study, it is shown that the environmental impact of the production of synthetic gas in the pilot plant is 21% lower than the production of fossil origin.

The current case of the pilot plant is that uses the conventional electricity mix (2018), making the electricity the most relevant environmental impact in the process. In a plausible industrial scenario, the electricity will come from a renewable source, then the impact would be reduced to a quarter.

The part of the process that had the most consumption in the pilot plant is the electrolysis of water. A technology of 37 kWh_e and 56.1% efficiency was used at the pilot plant. When the electrolyzer will be updated to a more advanced one with 81.1% efficiency, an impact reduction of up to 23.4% could be obtained.

Finally, synthesis gas from a pure CO_2 source has a 3-times greater impact than using a biogas source. However, an operation with an electrolyzer with more efficiency and the use of renewable energy diminishes the impact to a more promising value.

Overall, the combination of an advanced electrolyzer, a renewable electricity grid and biogas as carbon source reduces 85% of the climate change emissions. In line with the European Union decarbonization roadmap.

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